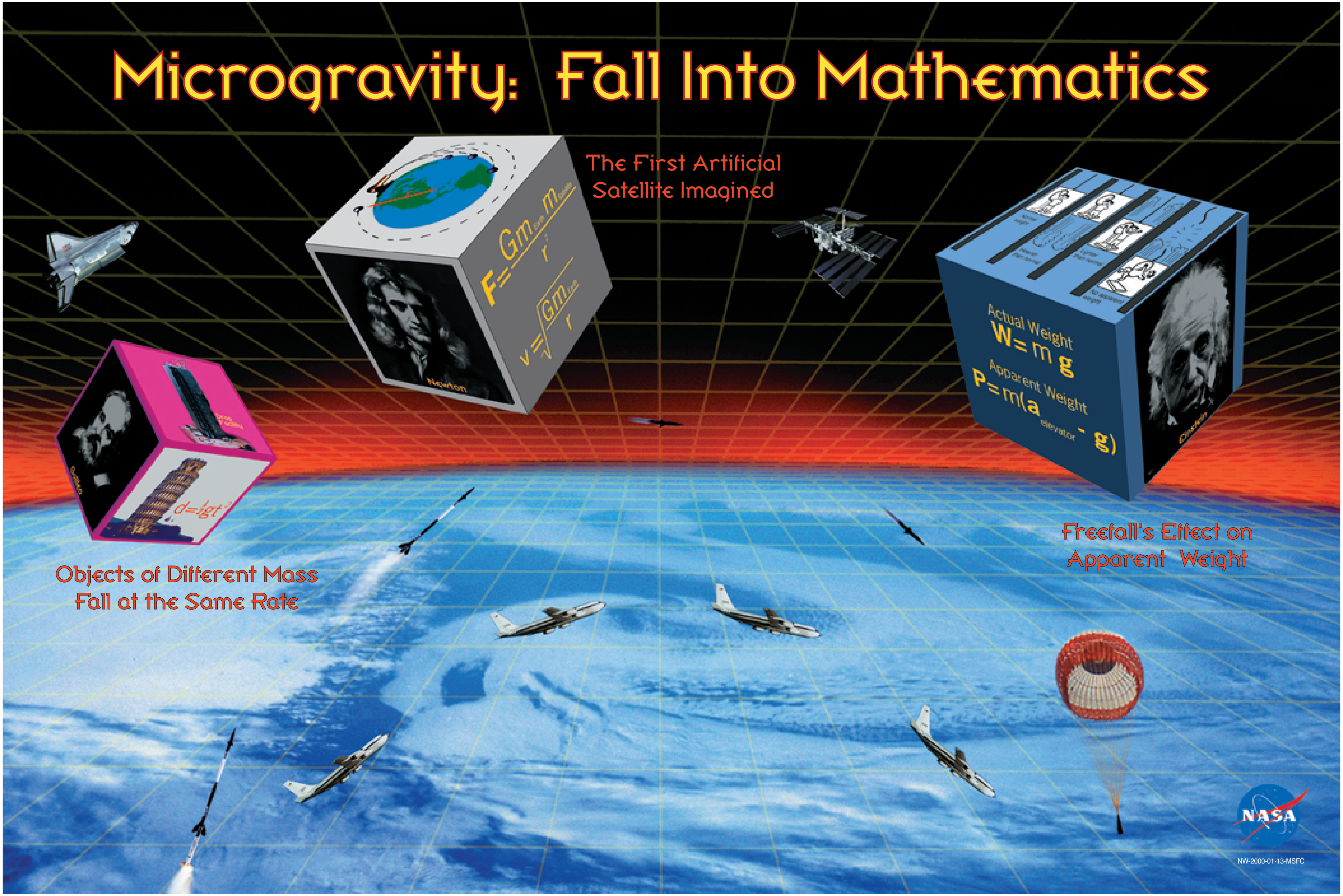

Microgravity: Fall Into Mathematics
The First Artificial Satellite Imagined
$F = \frac{G m_{Earth} m_{Satellite}}{r^2}$
$v = \sqrt{\frac{G m_{Earth}}{r}}$
Newton
Objects of Different Mass Fall at the Same Rate
$d = \frac{1}{2} g t^2$
Actual Weight
W = m g
Apparent Weight
P = m(a elevator - g)
Einstein
Freefall's Effect on Apparent Weight
NASA
NW-2000-01-13-MSFC

# Microgravity:
## Fall into Mathematics

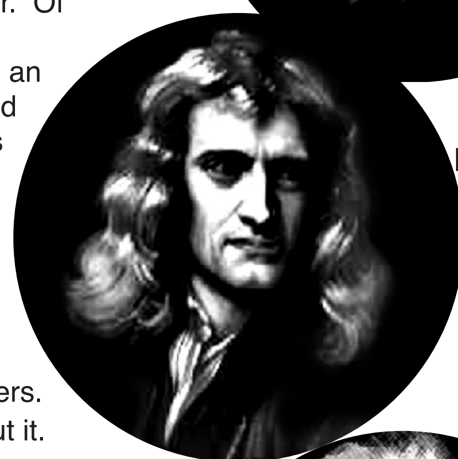
**"If I have seen far, it is because I have stood on the shoulders of giants."**
**Sir Isaac Newton**

Sir Isaac Newton wrote, "If I have seen far, it is because I have stood on the shoulders of giants." By this, he meant that his insights into the nature of gravity and motion were based on the work Galileo Galilei and others did before him. Likewise, Albert Einstein's work built upon Newton's. Without these three great minds, spacecraft might not be orbiting Earth today. The following pages provide a historical overview of each scientist's contribution to gravity and microgravity, and make mathematical connections to microgravity platforms and research.

Galileo Galilei
1564-1642

## Gravity

Gravity can be described as the pull objects exert on each other. Of course, an object has to be massive for the pull to be felt. How massive does it need to be? An object needs to be bigger than an elephant, a battleship, or a skyscraper - say in the neighborhood of a moon, a planet, or a star. The massive object closest to us is Earth.

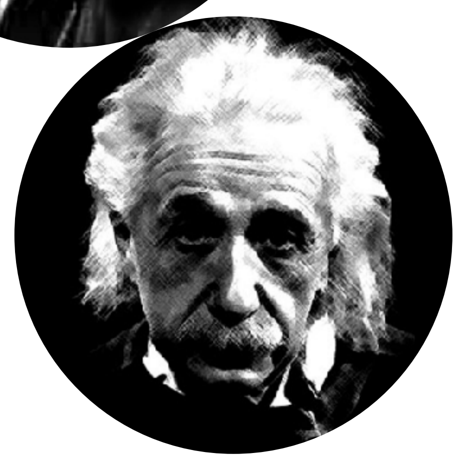


Isaac Newton
1642-1727

The effects of gravity are subtle and pervasive. Many people are surprised to find that the force of gravity affects things like the shape of a drop of water, toast dropping jelly-side down on the floor, a thrown baseball arching back to Earth, hot air rising while cool air sinks, and Italian dressing settling in layers. Gravity affects daily life so much that it is easy not to think about it.

## Great Minds Behind Microgravity

Some of the greatest minds in science and mathematics realized that an underlying force was at work when it came to falling objects. Galileo, then Newton, and later Einstein devised experiments to better understand the effects of gravity. Each of these scientist-mathematicians refined the research of his predecessors. Galileo's work with free falling objects, Newton's thought experiment for an artificial satellite, and Einstein's insight into the feeling of weightlessness during free fall, paved the way for the science of creating environments where some of the effects of gravity are reduced to a small amount, that is microgravity. Such environments allow scientists to research a number of phenomena normally affected by gravity.



Albert Einstein
1879-1955

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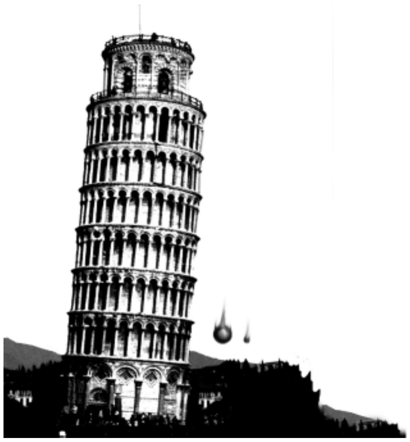
# Galileo Galilei
## 1564-1642

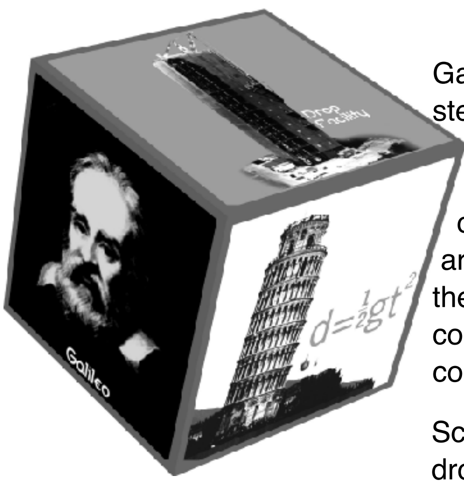


**Objects of Different Mass Fall at the Same Rate**
**A cannon ball and a musket ball, dropped from the Leaning Tower of Pisa, would hit the ground at the same time.**

While a professor in Pisa, Galileo was obligated to teach Aristotle's natural philosophy. However, Galileo's observations differed from Aristotle's theory that heavier objects fall faster than lighter objects, in proportion to their weight. Galileo reasoned that objects fall at the same rate. Legend has it that he dropped a cannon ball and a musket ball from the Leaning Tower of Pisa, and that the balls hit the ground at the same time. Unfortunately, this experiment is not documented in Galileo's writings.

Since then, scientists have carefully studied free falling objects, taking measurements with increasing precision. They have, indeed, found that, with the absence of air resistance, all bodies, regardless of size, fall with the same acceleration to Earth's surface. This eventually became known as the acceleration of gravity. On average, at Earth's surface the acceleration of gravity (1 g) is -9.8 meters per second squared ($m/s^2$).

$$d=(1/2)gt^2$$




Galileo also showed that there is a similarity between something moving at a steady velocity and something that is not moving at all: forces acting on them balance each other out. Galileo also discussed an aquarium on a ship: fish can swim in all directions regardless of whether the ship is anchored or sailing. For the fish, the ship's motion is irrelevant. Similarly, we walk around on Earth, rarely noticing Earth's motion as it rotates on its axis and orbits the Sun at 27,772 m/s. Einstein later used words similar to Galileo's in the context of falling systems. Galileo's concepts led to the creation of microgravity conditions and to Einstein's theory of gravitation.

Scientists are still doing experiments similar to Galileo's by dropping objects in drop towers. Below is some information about drop facilities in the United States and in Japan.

| Facility | Distance | Time |
|---|---|---|
| **Glenn Research Center** | **132 meters** | **5.2 seconds** |
| | **24 meters** | **2.2 seconds** |
| **Marshall Space Flight Center** | **100 meters** | **4.5 seconds** |
| **Japan Microgravity Center** | **490 meters** | **10 seconds** |

## Try This!

Calculate your own value for **g** using data from these four microgravity drop facilities (three at NASA and one in Japan). Use the equation above and the data in the table to solve for **g.** Note, **d** is distance and **t** is time.
Consider vertical motion to be positive upwards.

The real data will not produce the precise magnitude for **g** of 9.8 $m/s^2$. Why not? Note: making measurements and calculating results involve the concepts of accuracy and precision, significant figures, and orders of magnitude.

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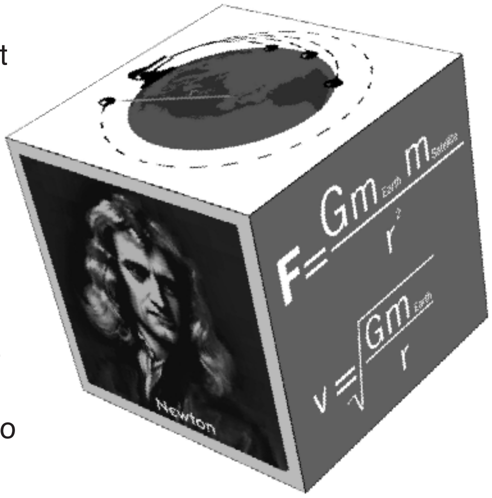
# Sir Isaac Newton

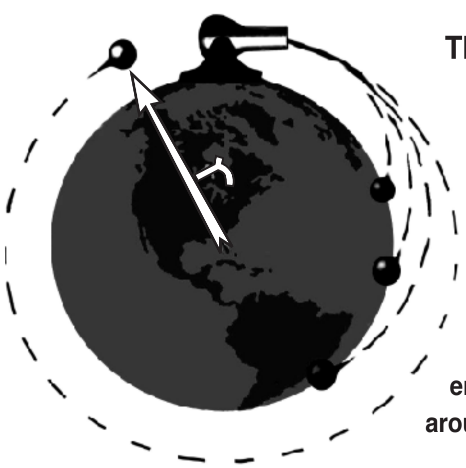
## 1642-1727

As a student at Cambridge, Newton retreated to the country when the university closed for 18 months because of the plague. While there, Newton drew upon Galileo's work as he discovered laws of motion and gravitation; he also invented the mathematical basis for calculus. His most famous scientific discoveries became known as the Universal Law of Gravitation and Newton's Three Laws of Motion. Together they describe the force of gravity and the motion of objects throughout the universe.




Newton reasoned that the shapes of planetary orbits around the Sun were due to gravity's presence. He expanded this conclusion to hypothesize how an artificial satellite could be made to orbit Earth. In his thought experiment, Newton imagined a tall mountain extending above Earth's atmosphere, so that air friction would not be a factor. He then imagined a cannon at the top of that mountain firing cannon balls parallel to the ground. The cannon ball would travel in a parabolic path, arching to Earth's surface, because of gravity.

With more and more black powder, the cannon ball path would lengthen. If the cannon could fire with enough force, the cannon ball would fall entirely around Earth, orbiting it. The Space Shuttle orbiters and the International Space Station are spacecraft that do, in fact, fall at fast enough rates to orbit Earth.




**The First Artificial Satellite Imagined**

**Newton thought how a cannon ball could orbit Earth: a cannon on top of a tall mountain would need to fire a cannon ball fast enough to fall entirely around Earth.**

## Try This!

Given the two equations to the right, calculate how fast a Space Shuttle orbiter and the International Space Station must travel in order to orbit Earth. Solve for velocity (**v**), using the data below.

$G$ = Universal Constant of Gravitation = $6.67 \times 10^{-11}$ $m^3/kg\ s^2$
$m_{Earth}$ = Earth's mass = $5.98 \times 10^{24}$ kg
$r$ = radius of Earth + spacecraft's altitude
$r_{Earth}$ = $6.37 \times 10^{6}$ m
Orbiter altitude = 290 km
International Space Station altitude = 350 km

$$F = G\frac{m_{Earth}m_{satellite}}{r^2}$$

$$v = \sqrt{\frac{Gm_{Earth}}{r}}$$

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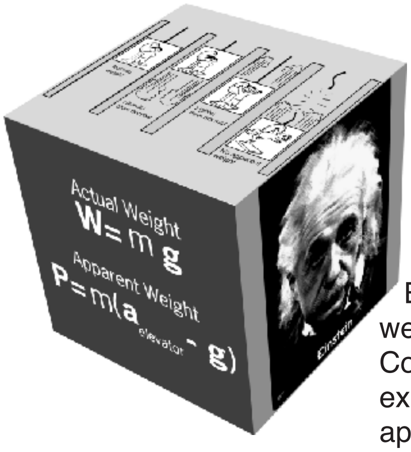
# Albert Einstein

## 1879-1955



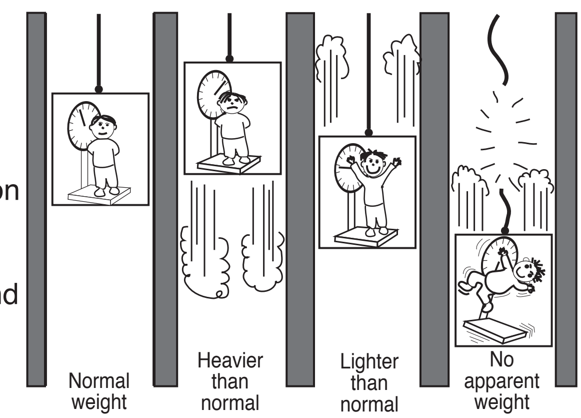

As a young man, Einstein graduated with a physics degree and struggled for a year to find a job. He finally found a position working for the patent office in Bern, Switzerland. There, he thought about physics and had the insight quoted on the left.

Einstein realized that in a state of free fall, a person or object would appear to be weightless. Actual weight is a measure of Earth's gravitational pull on mass. Conditions can be changed, however, to affect an object's apparent weight. One example is Einstein's free falling person: the person still has the same mass, but appears weightless. The illustration below shows how apparent weight changes for a person in an elevator that is stationary, accelerating upward, accelerating downward, and in free fall.

**"I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: 'If a person falls freely, he will not feel his own weight.'**

**I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation."**

If all safety mechanisms broke on an elevator, everything in the elevator would fall at the same rate of gravitational acceleration. The person pictured in the elevator would have no apparent weight, because he or she would no longer press down on the scale. Note: the picture to the right is misleading. The person and the scale would not spontaneously start floating. The person would need to jump up in order to float.




Similar feelings of becoming heavier and lighter are more obvious on a roller coaster. Rapid accelerations upward press riders back into their seat. Downward accelerations make a person feel lighter, like they would come out of their seat, if not for the safety restraints.

In the advent of the space age, Einstein's insight played a significant role in the development of microgravity research platforms. Platforms, like drop towers, are extensions of Einstein's thought experiment. Like Galileo and his fish, Einstein also realized that frames of reference and relative motion are vital concepts. In fact, Einstein's principle of relativity simply states that the laws of physics are the same in every inertial frame of reference. The far reaching implications of this statement are still being studied today.

## Try This!

Would your apparent weight in an elevator going up be the same as going down? Use the equations and data provided to calculate a person's apparent weight (**P**) in an accelerating elevator. Note: vertical accelerations are considered to be positive upwards.

Calculate weight for a 60 kg person in an accelerating elevator, if the elevator accelerates at:

(1)1m/s$^2$ (2)0.5m/s$^2$ (3)free fall

**F**= total force m= person's mass

**P**= apparent weight **g**= Earth's gravity

$\mathbf{a}_{elevator}$ = acceleration of the elevator

**W**= actual weight (mass x Earth's gravity)

# Microgravity

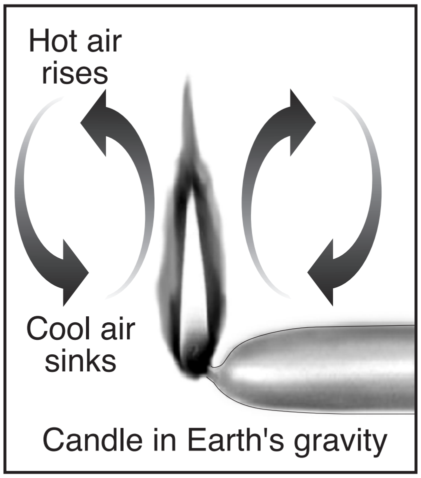
The environment where astronauts float in the International Space Station is an example of microgravity. Microgravity is a condition where some of the effects of gravity are reduced compared to those experienced on Earth. When in orbit, astronauts and the Space Station are actually in a state of free fall around Earth.

**Microgravity is an environment or condition where some of the effects of gravity are reduced compared to those experienced on Earth.**

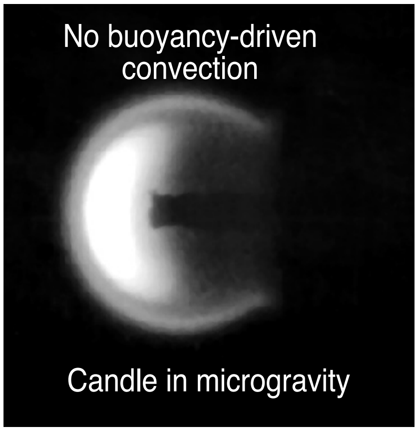
## Creating Microgravity

There are various ways to create microgravity. As mentioned before, one way to create microgravity is to put an object into a state of free fall. Researchers have devised facilities that use free fall to create microgravity conditions for varying lengths of time. These include drop facilities, parabolic aircraft, sounding rockets, and orbiting spacecraft.

Another way to find a microgravity environment is to go to a planet with a smaller gravitational field than Earth's. NASA is currently studying the feasability of building research facilities on Mars.



Candle in Earth's gravity



Candle in microgravity

## Microgravity Research Environment

Microgravity is a useful research environment because it reduces the effect gravity has on convection and sedimentation. These processes affect fluids and the way materials solidify. Microgravity provides a new research environment so scientists can study a wide range of phenomena.

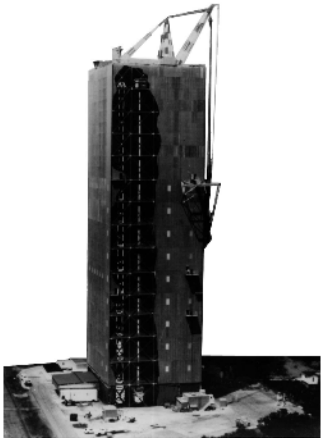
On Earth, buoyancy-driven convection occurs when less dense fluids rise and denser fluids sink. Boiling water on a stove is a common example of such convection. As water at the bottom of the pot heats, small bubbles of gas form that are less dense, and rise to the top. At the same time, cooler, denser water replaces the bubbles at the bottom, causing a flow pattern. Similarly, during combustion, hot, less dense products of a flame rise, and cooler, denser surrounding air sinks to the flame's base. In microgravity, buoyancy-driven convection is reduced, causing a candle flame to appear rounder and dimmer.

Sedimentation occurs when matter of different densities forms layers, with denser matter at the bottom. Italian salad dressing is a common example of sedimentation. However, in microgravity, fluids with different densities do not form layers. For example, water flowing through a pipe could contain pockets of air, instead of the water staying on the bottom and the air rising to the top of the pipe.

# Microgravity Platforms

Researchers use four types of platforms to create microgravity environments: drop facilities, parabolic aircraft, sounding rockets, and orbiting spacecraft.

http://microgravity.nasa.gov/NASA_Carrier_User_Guide.pdf



http://microgravity.nasa.gov/mf.html

## Drop Facilities

Drop facilities include drop towers and drop tubes. NASA Glenn Research Center has two drop facilities. One is 24 meters high, providing 2.2 seconds of microgravity. The other is 132 meters deep for 5.2 seconds of microgravity. The towers drop self-contained experiments with equipment, computers, and cameras on board. NASA Marshall Space Flight Center has a drop tube 105 meters high that allows molten metal droplets to be studied while they fall for 4.6 seconds.

http://microgravity.grc.nasa.gov/kjenks/kc-135.htm

## Parabolic Aircraft

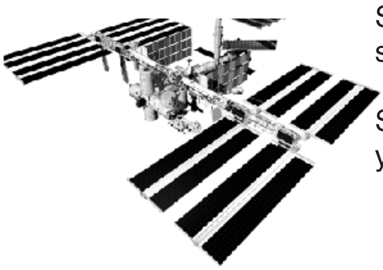
NASA's KC-135 is an aircraft that flies on a parabola-shaped path. The plane is referred to as the Weightless Wonder or the Vomit Comet for the nausea it causes. The aircraft has padded walls, foot restraints, hand holds, and devices for securing the experiments during flight. During research campaigns, the KC-135 can fly 40-60 parabolas. First, the plane climbs at a 45 degree angle to the horizon. Then, the pilot cuts back the engines to slow the aircraft and pitches the nose down to complete the parabola. The experiment and researchers experience 15-25 seconds of microgravity for each parabola. As the aircraft pulls out of the dive, the nose angles up, pulling 2 g, as it begins the next parabola.

http://www.wff.nasa.gov/~web/sndroc_pics.html

## Sounding Rockets

Like the KC-135, sounding rockets follow a parabolic arc. Unlike the plane, rockets like the Black Brant travel above the atmosphere. There the experiment compartment detaches to experience up to six minutes of free falling microgravity, before reentering Earth's atmosphere and parachuting to the ground. Sounding rockets produce higher quality microgravity conditions for longer periods of time; however, researchers cannot fly with the experiments.

http://station.nasa.gov



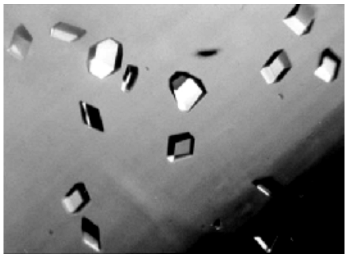
## Orbiting Spacecraft

Spacecraft like Space Shuttle orbiters and the International Space Station carry special laboratories into orbit for the longest periods of microgravity of all the platforms. The orbiters can carry experiments for up to 17 days. The International Space Station will have the capability to fly experiments for several months or even years.

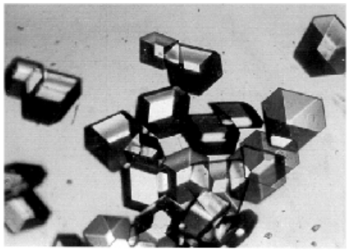
http://www.ksc.nasa.gov/ksc.html

# Microgravity Research

Scientists conduct microgravity research to better understand fundamental processes and structures that gravity affects. Microgravity research is conducted in the fields of biotechnology, combustion science, fluid physics, fundamental physics, and materials science.



Insulin crystals grown on Earth.



Insulin crystals grown in microgravity.

## Biotechnology

Biotechnology applies what scientists know about biology on Earth to solve problems in microgravity. For example, scientists use microgravity to grow higher quality protein crystals and viruses, and larger three-dimensional samples of cells and tissues than can be grown on Earth. Such research leads to advances in crop growth, medicine development, and artificial organs.

## Combustion Science

Combustion, or burning, is a chemical reaction that releases heat and soot. Microgravity scientists research fuels, the burning process, flame spread, and sooting. This research applies to energy efficiency, controlling pollution, forest fires, and general fire safety. Because 85% of the energy used on Earth is combustion based, the applications for industry are enormous.

## Fluid Physics

Fluids are liquids, gases, and particles that flow in response to force. The relevance of fluid research ranges from blood circulation to weather patterns, from engines to cosmetics. Microgravity fluid research examines the way fluids circulate, move with other fluids, respond to different forces, and wet surfaces, among other phenomena. Research results impact spacecraft cooling, life support, fuel tank design, aerosol sprays, gels, smoke, paints, and foams (like shaving cream).

## Fundamental Physics

Fundamental physics tests the laws that govern the physical world. In microgravity, this science researches laws affecting critical transitions between solids, liquids, and gases. Other areas of research examine the behavior of individual atoms (which affects atomic clocks) and Einstein's theory of gravitation.

## Materials Science

Materials science studies the properties of materials we produce to make things. A material's structure is based on the arrangements of its atoms. Research seeks to investigate and improve the properties of metals and alloys, electronic devices, glasses and ceramics, and polymers. As a result, the quality of soda cans, airplanes, computers, communications systems, and bioceramic artificial bones improves.

**For more information about microgravity research, visit these web sites:**

**Microgravity Research Program Office**
**http://microgravity.nasa.gov**

**Microgravity Research Division Headquarters**
**http://microgravity.hq.nasa.gov**

**Microgravity Science Division at Glenn Research Center**
**http://microgravity.grc.nasa.gov**

**The National Center for Microgravity Research on Fluids and Combustion**
**http://www.ncmr.org**

**For more information about NASA's Education Programs, visit:**
**http://education.nasa.gov**

**NASA Spacelink**
**http://spacelink.nasa.gov**

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# Answers to Try This!

## Galileo Try This!

Calculate your own value for **g** using data from four microgravity drop facilities. Consider vertical motion to be positive upwards.

Use this equation: $\mathbf{d} = (^1/_2)\mathbf{g}t^2$

Rewrite to solve for **g**. $\mathbf{g} = 2\mathbf{d}/t^2$

Solve the equation using the data in the table

| | d | t |
|---|---|---|
| 1. | 132 m | 5.2 s |
| 2. | 24 m | 2.2 s |
| 3. | 100 m | 4.5 s |
| 4. | 490 m | 10 s |

1. $\mathbf{g} = 2\,(-132\ \text{m}) / (5.2\ \text{s})^2 = -9.8\ \text{m/s}^2$
2. $\mathbf{g} = 2\,(-24\ \text{m}) / (2.2\ \text{s})^2 = -9.9\ \text{m/s}^2$
3. $\mathbf{g} = 2\,(-100\ \text{m}) / (4.5\ \text{s})^2 = -9.9\ \text{m/s}^2$
4. $\mathbf{g} = 2\,(-490\ \text{m}) / (10\ \text{s})^2 = -9.8\ \text{m/s}^2$

## Newton Try This!

Calculate how fast a Space Shuttle orbiter and the International Space Station travel in order to orbit Earth. Solve for velocity (**v**), using the data below.

G = Universal Constant of Gravitation = $6.67 \times 10^{-11}\ \text{m}^3/\text{kg s}^2$

$m_{Earth}$ = Earth's mass = $5.98 \times 10^{24}$ kg

r = radius of Earth + spacecraft's altitude

$r_{Earth}$ = $6.37 \times 10^6$ m

Orbiter altitude = 290 km

International Space Station altitude = 350 km

$$v = \sqrt{\frac{Gm_{Earth}}{r}}$$

$$\text{Orbiter: } v = \sqrt{\frac{(6.67 \times 10^{-11}\ \text{m}^3/\text{kg s}^2)(5.98 \times 10^{24}\ \text{kg})}{6.66 \times 10^6\ \text{m}}}$$

$$= 7.74 \times 10^3\ \text{m/s}$$

$$\text{Station: } v = \sqrt{\frac{(6.67 \times 10^{-11}\ \text{m}^3/\text{kg s}^2)(5.98 \times 10^{24}\ \text{kg})}{6.72 \times 10^6\ \text{m}}}$$

$$= 7.70 \times 10^3\ \text{m/s}$$

## Einstein Try This!

Would your apparent weight in an elevator going up be the same going down? Calculate a person's apparent weight (**P**) in an accelerating elevator. Note: Vertical accelerations are considered to be positive upwards.

**F**= total force

**W**= actual weight (mass x Earth's gravity)

m= person's mass

$\mathbf{a}_{elevator}$ = acceleration of the elevator

**g**= Earth's Gravity

**P** = apparent weight

$\mathbf{P} = m(\mathbf{a}_{elevator} - \mathbf{g})$

(1). Elevator's acceleration is 1 $\text{m/s}^2$.

| | |
|---|---|
| $\mathbf{a}_{elevator} = -1\ \text{m/s}^2$ (elevator down) | $\mathbf{a}_{elevator} = +1\ \text{m/s}^2$ (elevator up) |
| $\mathbf{P} = (60\text{kg})\,(-1\text{m/s}^2 - (-9.8\text{m/s}^2))$ | $\mathbf{P} = (60\text{kg})\,(+1\text{m/s}^2 - (-9.8\text{m/s}^2))$ |
| $= 528\ \text{kg m/s}^2$ | $= 648\ \text{kg m/s}^2$ |

(2). Elevator's acceleration is 0.5 $\text{m/s}^2$.

| | |
|---|---|
| $\mathbf{a}_{elevator} = -0.5\ \text{m/s}^2$ (elevator down) | $\mathbf{a}_{elevator} = +0.5\ \text{m/s}^2$ (elevator up) |
| $\mathbf{P} = (60\text{kg})\,(-0.5\text{m/s}^2 - (-9.8\text{m/s}^2))$ | $\mathbf{P} = (60\text{kg})(+0.5\text{m/s}^2 - (-9.8\text{m/s}^2))$ |
| $= 558\ \text{kg m/s}^2$ | $= 618\ \text{kg m/s}^2$ |

(3). Elevator is in free fall.

$\mathbf{a}_{elevator} = -9.8\ \text{m/s}^2$ (free fall)

$\mathbf{P} = (60\text{kg})\,(-9.8\ \text{m/s}^2 - (-9.8\text{m/s}^2))$

$= 0\ \text{kg m/s}^2$

### Online Evaluation

Please take a moment to evaluate this product at
**http://ehb2.gsfc.nasa.gov/edcats/educational_wallsheet**
Your evaluation and suggestions are vital to continually improving NASA educational materials.

Thank you.

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